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A Parametric Design Environment for Including Signatures Analysis in Conceptual Design

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ABSTRACT

System effectiveness has become the prime metric for the evaluation of military aircraft. As such, it is the designer's goal to maximize system effectiveness. Industry documents indicate that all future military aircraft will incorporate signature reduction as an attempt to improve system effectiveness. Today's operating environments demand low observable aircraft which are able to reliably eliminate valuable, time critical targets. Thus, it is desirable to be able to evaluate the signatures of a vehicle, as well as the influence of signatures on the systems effectiveness of a vehicle. Previous studies have shown that shaping of the vehicle is one of the most important contributors to radar cross section and must be considered from the very beginning of the design process. This research strives to meet these needs by developing a parametric geometry radar cross section prediction tool. This tool is envisioned to predict the radar cross section of the vehicle as well as the impact of geometry changes.

INTRODUCTION

Aircraft signatures have become increasingly important in modern conflicts. Low signatures help aircraft to avoid high loss rates, reach their objectives, and operate at high levels of system effectiveness. This section will further discuss the implications and importance of low observable designs.

Military aircraft design doctrine shifted after World War II and particularly during the Korean War. During these engagements, unacceptably high numbers of aircraft and crew were lost. The F-100 and A-1 were limited in the areas they could fly in Vietnam because of high loss rates (Ref. [1]). New aircraft designs and design techniques were created to assure that such high loss rates would not reoccur in the future. These advanced design techniques led to current survivability design methods including Low Observable technology popularly referred to as *stealth*. The benefits of these designs have been shown repeatedly, but one of the most famous examples was in Operation Desert Storm.

During the first few hours of Operation Desert Storm, F-117's flew through some of Iraq's most dangerous air defenses to attack targets in Baghdad. The F-117's faced modern integrated early warning and ground control intercept radars, advanced surface to air-missiles, and anti-air artillery as well as airborne interceptors and the advanced Kari integration system. The threats that the F-117 faced were so stiff that conventional aircraft were held back from Baghdad. The Nighthawk's Low Observable (LO) features minimized detection and tracking by the Iraqi defenses. After hundreds of sorties throughout the war, not a single F-117 was lost. The Gulf War demonstrated the effectiveness of LO designs as a survivability enhancement (Ref. [2]).

Furthermore, because LO vehicles require less support they are more capable. According to the Secretary of Defense's testimony to the Senate Armed Services Committee, eight F-117s or one B-2 can accomplish the same strike that would take more than 70 conventional aircraft (Ref. [3]). This can be graphically seen in Figure 1. For a constant strike mission, the LO aircraft, while more expensive individually, have a much lower system cost per target and thus a higher system effectiveness than their conventional counterparts. The Air Force believes that system effectiveness is the best overall metric for evaluating a military system. The Advanced Tactical Fighter (F22) design was developed and judged using system effectiveness as its criteria (Ref. [4]).

Low Observable vehicles are more difficult to detect, track, and shoot down and are thus more survivable. Increasing the survivability of an aircraft has dramatic effects on its effectiveness. A more survivable aircraft is safer during both peacetime and wartime operations. Over the lifetime of the design a more survivable aircraft is thus cheaper to operate since it will need to be replaced less frequently and it can attack more targets (Ref. [5]). According to Volpe and Schiavone,

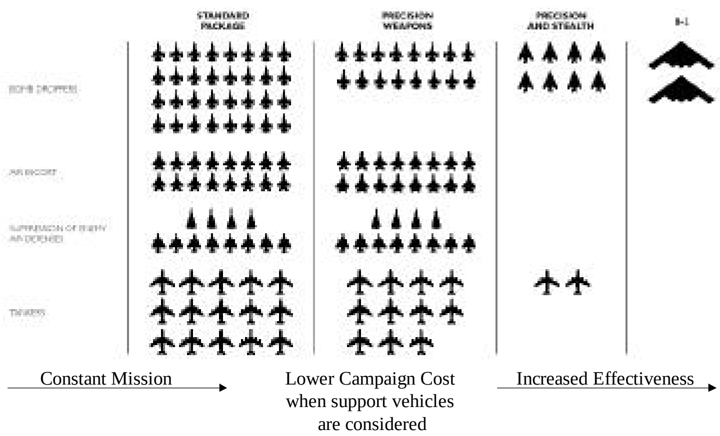

Figure 1: The Case for Stealth (Ref. [6])

"Linear changes in survivability produce exponential changes in force effectiveness. In Desert Storm, the allies flew 103,200 sorties with 2021 aircraft; this is an average of 51 missions per aircraft (Ref. [7])… For 51 sorties the difference between 98% and 99% P_s is the difference between 36% and 60% of the force surviving. This has a large impact on force effectiveness. The one percent increase in survivability produces a 26 percent increase in force effectiveness. This is a clear reason why survivability is a force multiplier (Ref. [5])."

A low observable design in this sense is more capable. It can safely fly where conventional aircraft cannot. In a world of time critical targets, low observable weapon systems become a necessity. Trade studies have often shown that as a vehicle becomes more stealthy, its detection range decreases and its operation envelope increases. Reducing signatures allows aircraft to penetrate enemy defenses. SAM site detection range is greatly reduced. Careful route planning can allow LO aircraft to take advantages of the geometry of the enemy SAM layout. As the operation envelope increases, the number of targets that the vehicle can attack increases, thus increasing the effectiveness of the weapon system (Ref. [2]).

According to Foulke (Ref. [8]), signatures reduction will be important to all future military aircraft designs. Because of the importance of signatures, it is important to be able to incorporate signatures analysis and reduction techniques into the aircraft design process.

> "All future weapon systems will have to consider LO technology during the concept formulation phase of the design process. Deciding whether or not to incorporate LO features, and if so to what extent, will have to be part of the design trade studies, but it is hard to imagine a new aircraft that will not feature some level of this technology (Ref. [8])."

This work aims to increase aircraft survivability by allowing designers to analyze the Radar Cross Section (RCS) of a vehicle and providing a methodology for incorporating this analysis into conceptual and preliminary design. A tool that links signatures analysis to conceptual design will vastly improve the knowledge available to military aircraft designers.

DEFINITIONS

To understand work in the military system effectiveness arena, it is first important to understand a few key terms. Aircraft survivability is "the capability of an aircraft to avoid and / or withstand a man-made hostile environment (Ref. [1])." Aircraft survivability, the probability of survival or P_s, is composed of two elements, susceptibility and vulnerability. Susceptibility, is the, "inability of an aircraft to avoid the radars, guns, ballistic projectiles, guided missiles, exploding warheads, and other elements that make up the hostile environment…(Ref. [1])." Susceptibility is measured by P_h, the probability that the aircraft is hit by a threat. Vulnerability consists of "the inability to withstand the damage caused by the hostile environment (Ref. [1])," and is defined by $P_{k|h}$, the probability of kill given a hit. Thus survivability can be expressed as:

$$\mathbf{Ps = 1- Ph\ Pk|h} \qquad (1)$$

This work focuses on reducing susceptibility and thus it is important to further examine the term. According to Dr. Ball, susceptibility can be broken down into several components: "(1) threat activity, (2) aircraft detection, identification, and tracking; and (3) missile launch or gun firing, propagator flyout, and warhead impact or detonation (Ref. [1])." The application of low observable technology falls into the aircraft detection, identification, and tracking category. Survivability can be further broken down as shown in Figure 2.

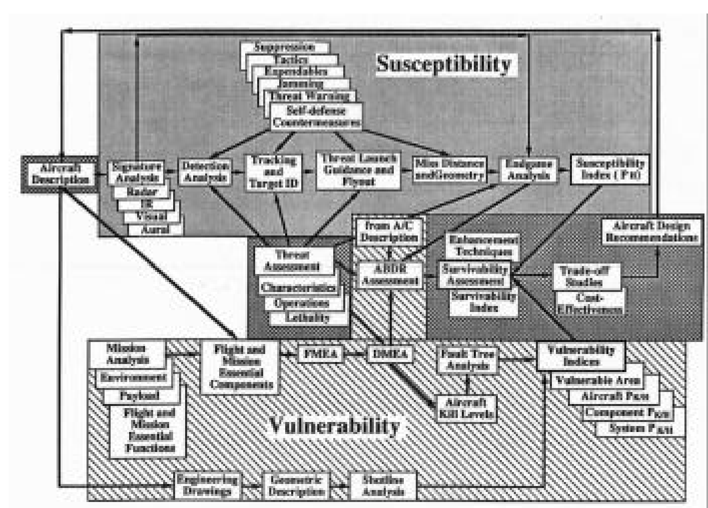

Figure 2: Components of Aircraft Survivability (Ref. [9])

Although signatures as a whole consists of signals in the radar, visible, infrared (IR), aural, and other frequency regimes, this work will focus primarily on radar signatures. Although the IR and visible regimes are important, it is felt that Radar is one of the primary tools used to acquire, track, and fire upon aircraft and thus is one of the most important frequency regimes for which to design.

CONCURRENT AIRCRAFT DESIGN

With system effectiveness and capability as motivation, it is clear that LO should be incorporated into the design of military aircraft, but how and where? There are several arguments for including LO analyses early into the conceptual design process. In this section the traditional paradigm shift will be discussed. Conceptual design is the stage of design with the most freedom, options, and excitement.

The Paradigm Shift, Figure 3, depicts a powerful concept, showing the cost reducing benefits of bringing high fidelity knowledge into the design process as early as possible. At the beginning of conceptual design, few decisions have been made and more freedom exists to make these decisions. Since few decisions have been made, little of the associated costs have been determined. However, little knowledge exists about the design to make an informed decision. Little high fidelity, physics based analysis work has been done to investigate alternatives. By bringing more knowledge earlier in the design process, designers can make more informed decisions. These better informed decisions will thus result in less expensive rework, dramatically reducing design costs. The key to this paradigm shift is to bring in more and higher fidelity information earlier in the design process where it can have the most impact on the final product (Ref. [10]). Signatures analysis should be brought into conceptual design where the knowledge it provides can be best used.

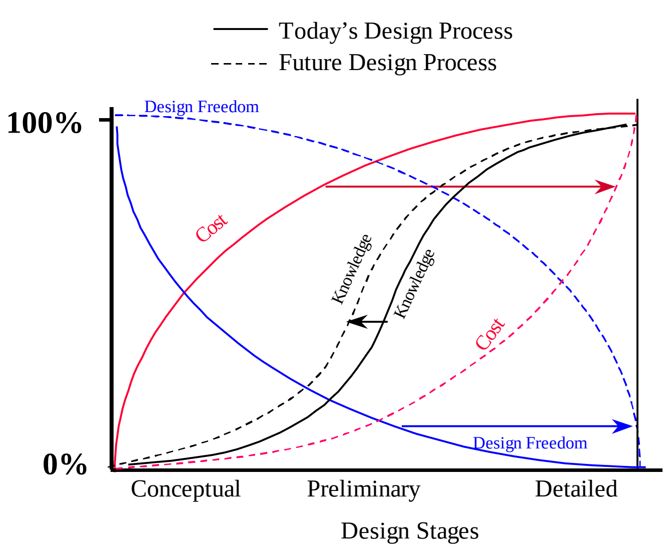

Figure 3: Paradigm Shift (Ref. [10])

Conceptual design is a unique environment that places demands on design tools. In conceptual design few of the details of the configuration have been determined. Because of the variety of options available at this stage, many configurations are usually investigated. Thus, a useful analysis tool should be able to handle a variety of configurations. Since each of the investigations requires an analysis using the design tool, run time can quickly escalate if the design tool is not quick. Exact time consuming answers are not as important as a quick 80% answer. That is, a tool that approximates the performance of a given design fairly well is more important than a tool that more accurately models the physics of a design, giving a more exact solution, but takes orders of magnitude longer to run. Conceptual design tools are used for design space exploration to identify promising regions that can be further analyzed. Often it is not important if a tool says that a design is the best or merely good. In fact, Ordinal Optimization (OO) has used this train of thought to quickly identify promising designs from a very large design space (Ref. [11]). OO is but one of many design space exploration tools that take advantage of speedy engineering analysis tools to efficiently identify promising regions for further analysis.

In addition to a need for speed, fine details are unknown at the conceptual design stage. An analysis tool should be able to either handle uncertainty in these unknown details or operate at a lower level of fidelity that avoids the unknowns. Traditionally tools operate at lower fidelity to achieve higher analysis speed, but with modern computational power (and certainly that of the future), analysis codes can address uncertainty and still provide reasonably quick answers. Finally, conceptual design is inherently interdisciplinary. A design decision can not be made in one discipline without consultation with all the others. For example, an aerodynamicist could not change the wing sweep angle without first consulting the structural, propulsion, systems, and signatures engineers. Conceptual level analyses need to be able to use and share information from/with other disciplines. Creating a common interdisciplinary parametric description of a problem eases data exchange between tools. With this technique, a few simple design parameters can be used to describe a wide variety of specific designs. Techniques like the Design of Experiments (DOE), can be used to do sensitivity analyses. Analysis of Variance and Paretto analyses can show key contributors to outputs of interest. To effectively use either the DOE or Paretto analysis tools, the inputs to the conceptual design tool should be parametric. In summary, conceptual design analysis tools in general need to be reasonably quick, be parametric, provide first cut accuracy, and be able to handle a low level of input fidelity.

Traditionally, conceptual design codes have used approximations, assumptions, historic data, or heuristics to accomplish their goals. To bring more knowledge earlier into the design process, physics based analyses are now being used. The authors have been unable to identify any historic based signatures code in the public domain. Most likely any such code, if it does exist, is either highly proprietary, classified, or unobtainable for this research. Luckily several physics based codes do exist, but are more geared toward higher end analyses. It is the hope of this research to demonstrate the process.

IMPORTANCE OF SHAPING

Signatures analysis should be integrated into the earliest stages of design to create an LO aircraft not only because this is where the analysis can have the most influence on a configuration, but also out of necessity. According to Stonier and Knott et all (Ref. [12 and 15]), Aircraft RCS reduction can be accomplished through shaping, Radar Absorbing Materials (RAM), passive cancellation, and active cancellation. Shaping and RAM are the most practical and cost effective (Ref. [12 and 13]). Furthermore,

> “ planform shaping is the most fundamental choice in the ‘clean sheet of paper’ design of any system with reduced RCS. Although the system RCS is composed of several sources, the *body configuration sets the ultimate lowest level achievable* for the system (Ref. [12]).”

Other sources agree, shaping is the most effective way to create a LO vehicle. For example, Stonier states,

> “The aerodynamic shape of the airplane is *the* most critical parameter in achieving a low RCS… Shaping must be performed in the initial aircraft design and should take precedence over most other aircraft design features in very low observable aircraft designs” [emphasis added] (Ref. [13]).”

RAM is frequency specific, often weighs a lot, and can be hard to maintain. For example the B2 stealth bomber, which extensively uses RAM, must be stored in a special (read expensive) climate controlled hanger to maintain the RAM. Additionally, most types of RAM are only effective over a narrow band of frequencies. RAM should be considered more of a Band-Aid to reduce an RCS hotspot than to reduce the RCS for an entire aircraft. Using RAM in such a manner would result in a heavy, inefficient vehicle. RCS reduction began in World War II with the application of various paints and coatings as RAM. However, these applications had minimal effect on the overall RCS of the vehicles since they were not incorporated from the outset of the design of the vehicle (Ref. [14]). Thus shaping should take precedence over RAM.

Shaping has been shown to be important in creating a Low Observable vehicle, but what is it? *Shaping is creating the physical geometry of the vehicle to orient surfaces so that the deflected energy travels away from the source radar* (Ref. [15]). Radar must receive signals reflected from the target aircraft to detect, track, and fire upon the target. Shaping aims to carefully control and minimize the energy reflected from the target aircraft. Shaping is mostly determined during conceptual design. After this stage of design, the aerodynamic shape is mostly frozen and it would not be possible to greatly reduce signatures by changing the shape.

> “RCS reduction technology can be applied to new or existing aircraft. However, applying it to an existing aircraft design does not allow for use of all the tools available for radar signature control and often imposes large weight and performance penalties. To provide the maximum benefit, RCS reduction must be incorporated as part of a vehicle’s initial design concept, because it affects every other design factor and technology involved in the aircraft’s development. Since RCS is the vector sum of the RCS’s of all the aircraft’s component parts, no feature can be designed without careful consideration of its impact on the total RCS. The aircraft RCS, moreover, can be no smaller than the RCS of its largest component. (Ref. [8]).”

As an example, the RCS of the Joint Strike Fighter (JSF) must be –30dB or 0.001 sq. meter, about the size of a golf ball (Ref. [16]). Such lofty RCS goals can only be attained using shaping to help control RCS from the earliest stages of design (as well as RAM and cancellation techniques later in the process). Since RCS analysis must become part of the conceptual design process, it would be wise to create an efficient, capable, and effective system for doing so.

FIRST PRINCIPLES OF RCS

Radar detects targets by evaluating the strength, timing, phase shift, and direction of energy returned to the detector as compared to the energy emitted from the transmitter. Since aircraft are not perfect reflectors, some of the incident energy is absorbed or deflected and does not return to the radar. The ratio of the scattered or reflected energy to the incident energy is called Radar Cross Section, RCS. RCS, quantified by the symbol, σ, is defined by the following equation (Ref. [12]):

$$\sigma = \lim_{R \to \infty} 4 \pi R^2 \frac{|E_s|^2}{|E_i|^2} \qquad \textbf{(2)}$$

> where, R is the distance between the source radar and the target, and E_s and E_i are the scattered and incident energy, respectively.

This paper does not intend to delve into lengthy explanations of the inner workings of radar. There are already several excellent books on the subject, such as those by Knott, Jenn, and Stimson. However, it is important to have a basic understanding of the physics of radar in order to understand how aircraft can be designed for reduced detectability.

RADAR RANGE EQUATION

The easiest way to see the effect of low observables on performance is through the radar range equation. Understanding the radar range equation is fundamental in understanding attempts to design aircraft that are difficult to detect.

$$R_{\max} = \left[\frac{P_t G^2 \lambda^2 \sigma L}{(4\pi)^3 P_{\min}} \right]^{\frac{1}{4}} \quad \textbf{(3)}$$

where

- P_t is the radar transmitter power
- P_{min} is the minimum receive signal threshold
- λ is the wavelength of the radar
- σ is the radar cross section
- L is a loss factor due to attenuation and inefficiencies
- G is the gain of the radar
- R_{max} is the maximum range of detection (Ref. [18]).

Note that for a given radar system, the radar range equation reduces to:

$$R = c\sqrt[4]{\sigma} \quad \textbf{(4)}$$

where c is a constant composed of factors above.

In other words, to reduce the detection range by a factor of two, the radar cross section of the vehicle must be reduced by a factor of 2^4 or *16*. Moreover, to reduce the detection range by a factor of 10, the RCS must be reduced by a factor of 10,000. Significant reductions of RCS must be made to significantly limit detection range. While aircraft such as the B-2 and F-117 have been designed with very low RCS, this was done while sacrificing other disciplines. Below, Table 1 shows the effect of RCS Reduction (RCSR) on detection range. As an example, if a SAM site could detect an aircraft at 100 miles, a 20dB (99%) reduction in the RCS would translate into a new detection range of 32 miles.

Table 1: Detection range as a function of RCS reduction (Ref. [12])

Radar Cross Section Reduction (RCSR) %	RCSR (dB)	Detection Range
0 %	0 dB	100 (arbitrary)
90 %	10 dB	56
99 %	20 dB	32
99.9 %	30 dB	18
99.99 %	40 dB	10

Further explanation of radar analysis will be given later in this paper. This section was meant to give a brief introduction into fundamental elements of radar detection.

The goal of this project is thus to link conceptual design to Radar Cross Section estimation. Signatures are and will be an important part of all military aircraft designs. Signatures information can be combined with information from other design level analyses to create a tool that shows geometry tradeoffs between the disciplines. However, neither signatures reduction nor increased survivability are the end goal of this project. The end goal is to create both a methodology and a tool for evaluating and designing a system that performs in its useful environment.

PHYSICS OF THE PROBLEM

With this goal in mind, the physics of the problem will now be further explored. The first step in this process is to understand the threats that an aircraft might face. Next one should understand how to evaluate the detectability for a given threat. And finally, design methodologies should be developed to incorporate this knowledge.

THREATS

Aircraft face a variety of threats depending on their mission, the particular enemy, and the tactics of both friend and foe. Each of the threats has specific characteristics. In turn these characteristics lead to the best way to minimize the chance of being detected, tracked, and fused to by the weapon system. This paper only examines radar systems, however a variety of other systems exist such as: infrared, visual, and aural.

There are two basic types of radar-monostatic and bistatic. Monostatic radar has both the receiver and transmitter at the same location. Bistatic radar has one or many receivers located away from the transmitter as seen in Figure 4. For monostatic radar, we are interested in the amount of energy transmitted back to the source, called backscatter (Ref. [14]). For bistatic radar we are interested in the amount of power transmitted to the receiver. Monostatic radar systems are much more common and will thus be the focus of this work. Limiting the threats to radar systems for this work, each system operates on different frequencies and with different output power and receiver sensitivity. Table 2 contains a brief summary of existing threats and their specific radar frequency ranges.

Radar frequencies range from single digit to 300,000,000 MHz. Physical size, weight, and power limitations constrain airborne radar to frequencies that range from .4 to 40 GHz. A majority of airborne military threats operate

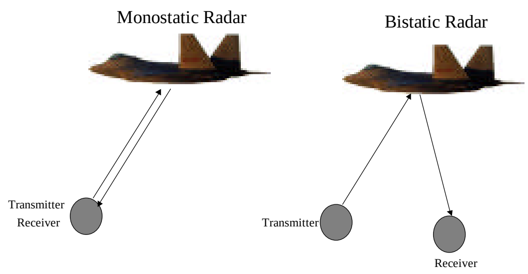

Figure 4: Monostatic versus Bistatic radar

Table 2: Radar Frequency Bands and their Uses (Refs. [2, 12, and 17])

Band Designation	Frequency Range (GHz)	Usage
HF	0.003 – 0.03	Over-the-Horizon Surveillance
VHF	0.03 – 0.3	Very Long Range Surveillance
UHF	0.3 – 1	Very Long Range Surveillance
L	1 – 2	Long Range Surveillance, Enroute Air Traffic Control
S	2 – 4	Medium Range Surveillance, Terminal Traffic Control
C	4 – 8	Long Range Tracking
X	8 – 12	Short Range Tracking, Missile Guidance, Airborne Intercept
K_u	12 – 18	High Resolution Mapping
K	18 – 27	Little Used (Water Vapor Absorption)
K_a	27 – 40	Very High Resolution Mapping
Millimeter	40 – 300	Experimental

in the X and Ku bands (8 to 18 GHz), with a high percentage of the radars operating at the 3 cm. wavelength. The 3 cm wavelength is attractive because it offers a compromise between size and performance and is also readily available. Atmospheric attenuation is relatively low at that wavelength. While early warning, search and reconnaissance radar operate at low frequency, they do not have the resolution to direct weapons. Higher frequency Fire and Control radar typically operate in the X and Ku bands to generate the resolution necessary for accuracy (Ref. [17]).

As can be seen in Figure 5, RCS exhibits three different regions of behavior, dependent on frequency. In the low frequency, Raleigh region, variations in shape do not

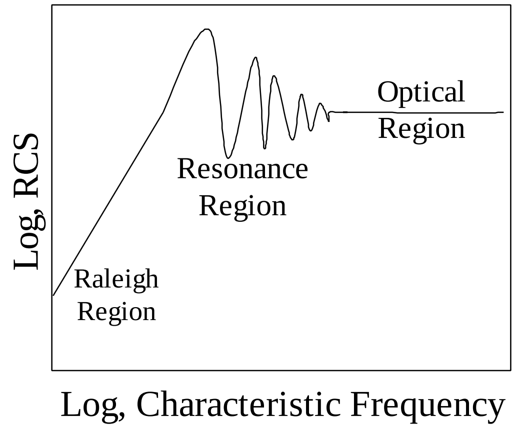

Figure 5: Radar Cross Section of a Sphere (Ref. [18])

greatly affect scattering characteristics. According to Jenn, σ varies as $1/\lambda^4$ (where λ is wavelength) in this region. In the middle frequency, Resonance Region, small changes in phase or frequency produce large variations in σ. Finally, in the upper frequency region, σ is highly dependent upon orientation of the body with respect to the radar, however, the σ versus frequency curve is flat and nearly independent of wavelength (Ref. [18]). Most importantly, smooth aircraft sized objects, examined by the typical 8 to 18GHz frequency range, will fall into the optical region shown above.

In addition to frequency, it is important to consider where the threat will be relative to the aircraft. Threat sectors are highly dependent on aircraft mission and enemy weapon systems but a few are shown Table 3. As an example, a high altitude bomber flying against a Surface to Air Missile (SAM) site would have a threat sector of a hemisphere underneath the aircraft. A low altitude, ground-hugging, strike mission would primarily be concerned with the front and rear sectors as anything to the sides or below would be flown past too quickly to be much of a threat. The upper sector could be a threat if an AWACS type aircraft was in the area. In general the threat sectors exposed during a mission are derived using common sense.

Table 3: Threat Sectors

Mission Type	Primary Threat Sector
High Altitude Bomber	Lower sector for anti-aircraft artillery, frontal sector for SAR, upper sector AWACS
Low Altitude Strike	Frontal sector, rear sector

SCATTERING MECHANISMS

There are several different scattering mechanisms that are prevalent in aircraft radar cross section engineering. Jenn has classified these mechanisms as reflections, diffractions, surface waves, and ducting. It is important to understand the basic mechanisms of scattering before complex aircraft analyses can be completed (Ref. [18]).

Reflections include the bounce of a wave off a surface according to Snell's law. Multiple bounces can occur off of multiple reflectors. For example, Figure 6 shows a right angle corner reflector with the associated reflection mechanism. In general, reflections produce directional, strong returns and are the easiest to reduce in early stages of design (Ref. [18]).

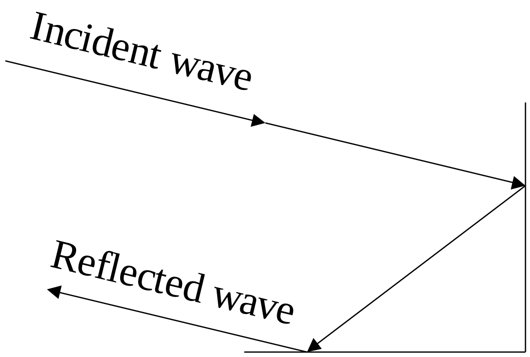

Figure 6: Reflection Mechanism

Diffractions occur at discontinuities like those at edges, tips, or abrupt changes in materials. Although diffractions are a second order effect compared to those of intense reflections, diffractions radiate over a wide range of directions. Because they spread radiation in so many directions, they are often a source of multi element scattering. If reflections have been minimized, the relative importance of diffractions increases. The diffraction mechanism is shown in Figure 7 (Ref. [18]).

Electrical currents induced by the incident wave flow through a body and cause surface waves. The body acts much like an electrical wire. Since electrical currents and radiation are inherently linked according to Maxwell's equations, these induced currents themselves radiate waves. There are several types of surface waves. If the currents travel along slender bodies or along edges, then the waves are called travelling waves. If the waves travel along curved surfaces, where they diffuse and wrap around a body, then they are called creeping waves. If the waves radiate from a flat surface then they are called leaky waves. Finally, if a wave encounters an abrupt change such as an edge or change in material, the wave will reflect and continue propagating. The strength of the surface wave returns can be relatively large but can be minimized by limiting edges and corners and by careful choice of electrical constants of the surfaces (Ref. [18]).

Ducting or waveguide modes, occur in (semi-) enclosures. Waves entering the enclosure reflect multiple times within the structure, finally emerging. Because of the multiple reflections, diffractions, and surface waves that can occur within the enclosure, multiple waves will emerge in many directions. Because the returns broadcast in many directions, they are not as strong as reflections, but they can emit a large amount of radiation (Ref. [18]).

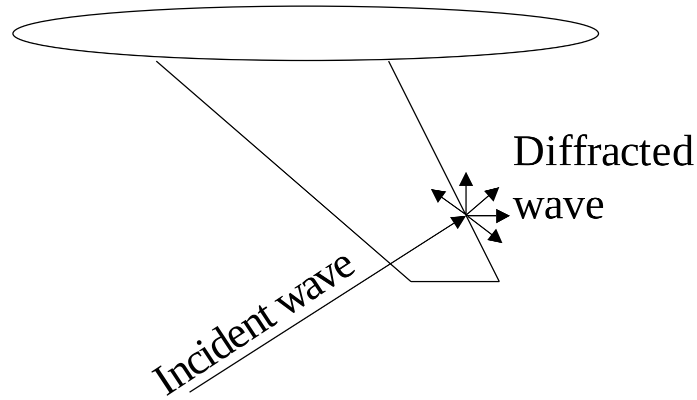

Figure 7: Diffraction Mechanism

Although the various radiation mechanisms can be classified separately, they often interact with each other. For example an incident wave could reflect off of a fuselage, diffract off of a trailing edge and enter a cavity (Ref. [18]). It is also important to realize that all of these phenomena have associated phase angles. Thus both constructive and destructive interference can occur due to the phase of the waves interacting with each other.

RADAR CROSS SECTION PREDICTION METHODS

With this basic understanding of how radar returns are formed, we will now focus on how to predict the returns. James Maxwell first formulated the physics of electromagnetic waves. However, just like the aerodynamic Navier Stokes equations, the Maxwell equations are difficult to solve exactly. In fact, exact solutions to these equations only exist for a few specific simple geometric shapes and certainly not for complex, full aircraft configurations. Thus several approximate solutions have been developed to help quickly model RCS (Ref. [14]). These approximate solutions make various assumptions that limit the range of validity of the solution, but greatly ease and speed the analysis process. In general the development of RCS prediction techniques evolved from antenna engineering.

PHYSICAL OPTICS THEORY

Physical optics approximates the induced currents in surface of the aircraft by setting them to be proportional to the incident magnetic field strength on the illuminated side of the body using geometrical optics. The technique sets the currents on the shadow side of the body to zero. Once the currents are known, the integrals can be easily solved. The method assumes the target is in the far field and is electrically large, at least 10 wavelengths in size. It does not model surface waves, but can be used in either the frequency or time domains. Errors increase in the transition between the shadow region and the illuminated region because of the abrupt change in currents (Ref. [18]).

In this case, the prediction technique will be used in the conceptual design environment where large numbers of designs of vastly different shape and with associated uncertainty will be examined. Additionally, the prediction technique should be relatively accurate over the most likely encountered threat frequencies, 1-18 GHz. Based on these needs and recommendations from experts, Physical Optics Theory appears to be the most desirable analysis technique.

GTS/TRACK OVERVIEW

Georgia Tech Research Institute's (GTRI) GTS/TRACK primarily uses the Physical Optics to calculate RCS for input targets (Ref. [19]). Developed in the 1980's and refined in the 1990's, GTS/TRACK can now analyze and simulate

> "complex targets in a multipath environment, with the capability of modeling various radar signal processor types, including amplitude or phase monopulse seekers to predict angle tracking errors, a flexible split-gate range tracker model, and prediction of target radar cross section distributions for input to probability of detection models for constant false-alarm rate (CFAR) surveillance radars in a clutter environment (Ref. [19])."

Targets are modeled as a set of geometric shapes, called primitives, and analyzed individually. The target RCS is then the coherent, vector, sum of the individual scatterers. The model captures both constructive and destructive interference with coherent summation. The individual returns, except for specific multiple bounce primitives, are calculated using physical optics integrals. The return for specific multiple bounce primitives is calculated using a combination between geometrical optics and physical optics. The higher order effect of edge diffraction can be modeled by creating a separate geometric model containing only the edges of the aircraft. The Method of Equivalent Currents (MEC) is then used to analyze the edge model to obtain the additional diffraction scattering. The effects of various materials can be calculated by modeling the dielectric and surface properties. GTS allows either/both the target and source radar to move and rotate independently in 3D space. Periodic or ground hugging maneuvers can be modeled. The capabilities of GTS are more advanced than described here and will not be fully utilized in this research (Ref. [19]).

GTS uses high frequency asymptotic methods. These techniques are only valid for individual scatterers that are large with respect to the wavelength of the threat radar. Thus it is important that plates used in the models are of the proper minimum size. GTS assumes that the threats are in the far field. For the purposes of this study, this assumption is perfectly valid. Additionally, GTS assumes a planar wave incident to the scatterer (Refs. [19, 20). The equations used by GTS to predict RCS will be further explained in a later section.

GTS geometry input comes from another GTRI program, MAX, which does 3D modeling using various primitives. MAX also contains links to an IR analysis tool, GTSIG. Although this work does not investigate IR signatures, it is important to realize that it would be relatively easy to expand the study by simply analyzing IR using GTSIG. Parts of the inputs for IR analysis are already provided by MAX and are the same for RCS analysis (Ref. [21]).

GTS has its own programming language, GCL. This language allows for simple automation of the program, allowing the user to run the program in batch mode. This is perfect for running multiple design cases or even a sweep of target viewing angles. The GTL language is an extension of the MAX script language, MCL, so learning one language facilitates learning the other. These scripting languages are ideal for running multiple cases in Designs Of Experiments (DOE).

PRIMITIVES

MAX defines and GTS analyzes geometric primitives, simple component geometries, to model a complex body. The two codes examine the following primitives: complete or total ellipsoids, triangular and quadrilateral plates, right or circular frusta, dihedrals, trihedrals, tophats, and edges. For example an aircraft could be modeled using a cone for the nose, a cylinder for the fuselage, and a series of flat plates for the wings and tails. Obviously this is an over simplification, but this shows the use of individual primitives to model a more complex target. The return for each of the component primitives is calculated independently and coherently added to find the total for the vehicle. A separate model can be developed using dihedrals and trihedrals to model edge effects. This thesis will not examine second order effects such as edges, instead focusing on the primary effects of shaping on RCS. Below are a few examples of the primitives MAX and GTS use as well as an example of a complete aircraft assembled from the primitives.

GTS EQUATIONS

The following section describes the formulas used by GTS to predict RCS.

Coherent, also known as vector, summation is as follows:

$$s = \left[{}_{i=1}^{n} W_i \sqrt{s_i}\right]^2 \qquad \textbf{(5)}$$

Where n is the number of scatterers, σ_i is the complex scattering value for surface I, W_i is the weighting factor, a number between zero and one that accounts for the reflectivity of a surface due to material properties such as dielectrics and Radar Absorbing Material (RAM) (Ref. [20]).

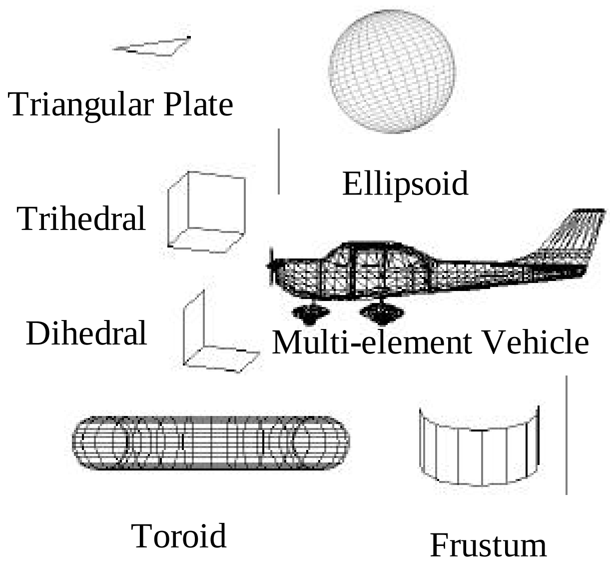

Figure 8: MAX and GTS Primitives in Use

Physical optics equations for bistatic scattering:

$$\sqrt{s} = \frac{\pm ik}{\sqrt{p}} \exp\left[ik\vec{r}_0 \cdot \left(\hat{i} - \hat{s}\right)\right] I$$
$$I = \int_A \hat{n} \cdot \hat{h}_i \times \hat{e}_r \exp\left[ik\vec{r} \cdot \left(\hat{i} - \hat{s}\right)\right] da \quad \textbf{(6)}$$

where the wave number of the incident wave is k=2π/λ, i = sqrt (-1), r_0 is a vector that goes from the origin to a reference point on the scatterer, $\hat{i}$ and $\hat{s}$ are unit vectors that point in the directions of the incident and scattered waves, $\vec{r}$ is a vector that goes from the scatterer reference point and sweeps over the region A, and $\hat{n}$ is an outward pointing unit vector from the element of integration da.

The integration is only performed on surfaces illuminated by the incident wave (Ref. [20]).

Fortunately, many simple shapes have closed form solutions for the integrals. This research only makes use of flat triangular plates and thus only the formulas for this primitive will be shown.

For a triangular flat plate this equation simplifies to:

$$\sqrt{s} = \frac{\hat{n} \cdot \hat{e}_r \times \hat{h}_i}{\sqrt{p}T} e^{(ik\vec{r}_o \bullet \vec{w})} \left\{ p \cdot a e^{(ik\vec{r}_a \bullet \vec{w})} \left[\frac{\sin(\frac{1}{2}k\vec{a} \cdot \vec{w})}{\frac{1}{2}k\vec{a} \cdot \vec{w}} \right] + \hat{p} \cdot \vec{b} e^{(ik\vec{r}_b \bullet \vec{w})} \left[\frac{\sin(\frac{1}{2}k\vec{b} \cdot \vec{w})}{\frac{1}{2}k\vec{b} \cdot \vec{w}} \right] + \hat{p} \cdot \vec{c} e^{(ik\vec{r}_c \bullet \vec{w})} \left[\frac{\sin(\frac{1}{2}k\vec{c} \cdot \vec{w})}{\frac{1}{2}k\vec{c} \cdot \vec{w}} \right] \right\} \quad \textbf{(7)}$$

where

$$\vec{w} = \hat{i} - \hat{s} \quad \textbf{(8)}$$

$$\hat{p} = \frac{\hat{n} \times \vec{w}}{\left|\hat{n} \times \vec{w}\right|} \quad \textbf{(9)}$$

$$T = \left|\hat{n} \times \vec{w}\right| \quad \textbf{(10)}$$

If T=0, a singularity would occur so instead the following equation is used:

$$\sqrt{s} = \frac{\hat{n} \cdot \hat{e}_r \times \hat{h}_i}{\sqrt{p}} e^{(ik\vec{r}_o \bullet \vec{w})} A \quad \textbf{(11)}$$

$$\hat{n} = \frac{-\hat{a} \times \vec{c}}{\left|\hat{a} \times \vec{c}\right|} \quad \textbf{(12)}$$

and $\hat{a}$, $\hat{b}$, and $\hat{c}$ are unit vectors along the edges of the triangular plate. Thus $\hat{n}$ is the outward pointing normal unit vector for the triangular plate. As in the generic case, r_0 points from the origin to the reference point on the scatterer. In this case the reference point is the centroid of the triangle. $\vec{r}_a$, $\vec{r}_b$, and $\vec{r}_c$ are vectors that point from the centroid to the midpoints of the sides of the triangle. A is simply the area of the triangle (Ref. [20]).

In using these formulas it is important to bear in mind a few assumptions. To simplify coordinate system transformations, the following are assumed:

- Cartesian coordinate system
- Distances much smaller than Earth's radius
- Target lies on Earth's surface
- Target allowed to move, but radar is stationary(Ref. [20]).

PROPOSED PROBLEM SOLUTION

PRELIMINARY METHODOLOGY LAYOUT

Preliminary research into this work has yielded the following methodology. A series of computer codes, linked together using scripts, has been used to create a parametric aircraft geometry, analyze it, and evaluate the results. It is important to realize that this method is independent of specific computer codes chosen to perform each task. This benefit of this research is not in linking computer codes to analyze RCS, it is in developing a methodology to parametrically incorporate signatures analysis into conceptual design. Bearing these facts in mind, Figure 9 shows the basic program flow. The solid lines detail completed links, while the dashed lines further outline a roadmap that could be used to increase the capabilities of this research.

This paragraph will describe the basic program flow pictured in Figure 9 in generic terms. A parametric aircraft geometry describes an aircraft that is created in a 3D CAD modeling tool. The surface of the model is then tessellated into a series of triangles by a CFD grid tool. The triangles are then translated into a format that can be read by an RCS analysis tool and analyzed. The vehicle RCS is translated into a probability of detection, P_d. Additionally, the method allows for additional analyses to be incorporated, but this thesis will not examine them due to time and scope constraints. Aerodynamics, IR, synthesis and sizing, and other disciplines can be incorporated as shown in Figure 9. Preliminary computer codes have been selected to demonstrate the basic methodology and to allow specific applications to be run. The next few sections will describe this process in more detail.

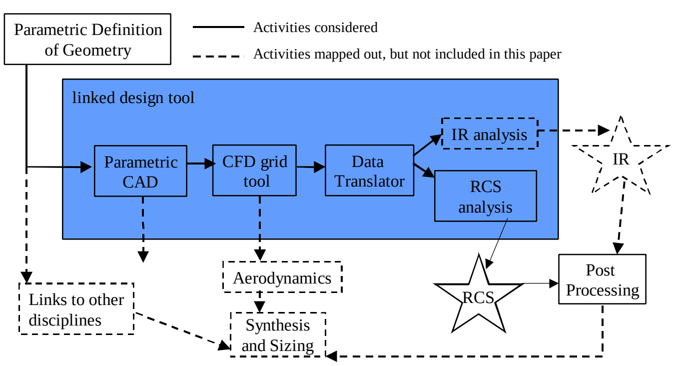

Figure 9: Program Flow

PARAMETRIC DEFINITION OF GEOMETRY

The analysis starts with a parametric definition of an aircraft. Such a definition consists of parameters such as wing area, aspect ratio, and taper ratio; nose shape parameters; tail area, aspect ratio, and taper ratio; etc. The parametric definition could be as complex or simplistic as desired. Canards, complex engine inlets, and other features could be parameterized. By varying the parameters for the design a wide variety of configurations can be modeled. For example, Figure 10 shows how a supersonic configuration could be parameterized and Figure 11 shows a variety of the configurations possible when the wing parameters are varied.

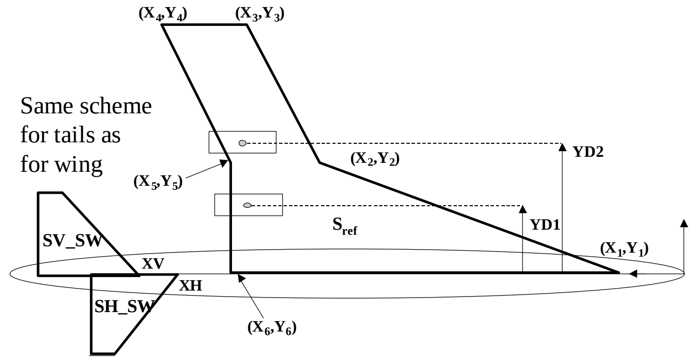

Figure 10: Parameterization

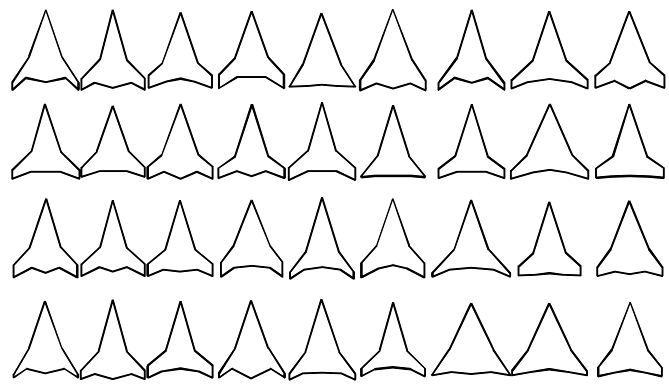

Figure 11: A Few of the Supersonic Wing Configurations Possible with Parameterization

COMPUTER AIDED DESIGN

Rapid Aircraft Modeler (RAM) is used to create a three dimensional aircraft from parametric input files. RAM was developed as a parametric CAD tool oriented towards conceptual design for the NASA Ames Systems Analysis Branch by Sterling Software and members of the internal NASA development team. The code is ideal for conceptual design because with only a few mouse clicks or other inputs it is possible to quickly model a wide variety of aircraft. This is a far less detailed process than using a full featured CAD tool such as CATIA. Additionally, predefined airfoils, wings, fuselages, engines, inlets, and nozzles are included in RAM where they would have to be created from scratch or from a library in a traditional CAD package. Since less detail of the configuration is known at the conceptual design stage than at later stages of design, the ability to quickly model a geometry without having to worry about excessive detail is very useful. Several useful utilities such as wetted area, volume, aerodynamics, and center of gravity calculations are internal to RAM (Ref. [22.

RAM has several output formats, one of which is particularly useful for this application. RAM can output input files for the CFD grid tool FELISA, the next stage of the RCS analysis process discussed here. Additional output formats are geared to other aerodynamic analysis tools such as VORLAX, HAVOC, and FPS3D (Ref. [23]).

RAM has a few limitations on its capabilities. It cannot model every aircraft type or geometry. It cannot model faceted surfaces, nor can it model blended surfaces. Both of these geometry types have been used in previous LO designs. However, the current trend has been away from faceted bodies and towards more easily modeled curved surfaces. Additionally, the blending of surfaces is a higher order effect than the basic geometry of the vehicle and could be examined at later stages of the design. Creativity could be used to model such design features as covered inlets and buried exhausts. Another limitation is that RAM is GUI based and thus not conducive to scripted automation. Fortunately, the authors have access to the source code for the program and it may be possible to automate RAM to reduce repetitive "user in the loop" workload.

Thus, the purpose of RAM is to model aircraft geometry. The program can either read in a predefined input file (generated from a DOE or otherwise) or create a geometry from scratch with user input. Once the 3D model is defined, RAM can output the FELISA input file for the next stage of the process.

CFD GRID TOOL

Although it is possible to create rough aircraft configurations using primitives in MAX, an automated approach is necessary to run DOE or complicated geometries. A CFD grid tool can automatically triangulate surfaces provided by the CAD tool. FELISA was preliminarily chosen to fulfill this role. FELISA is a set of computer tools developed for NASA Langley Thermal Loads Branch that create unstructured tetrahedral meshes and that will be used to automatically create triangular patches for MAX. For this project only the SURFACE tool, a triangular surface grid generator, will be used. The routines are automated and should work for virtually any configuration developed in RAM. TOFEL and other scripts developed at NASA AMES have linked RAM to FELISA, thus automating the link between the geometry created within RAM and the tessellation produced by SURFACE. NASA AMES has also linked a full potential solver, FPS3D to these two tools (23 page 3-4). Since a link is already used to create a surface grid in this research, the method could be expanded further to include creating a volume grid to use in a CFD analysis on the geometry in question. CFD, like FPS3D or another code, could be used to tradeoff aerodynamics and RCS. Figure 12 shows an example surface grid.

There are several distinct advantages to using FELISA. The tool is already linked to RAM. Using the pre-linked code can save significant time and energy. It works with RAM and creates groups of triangles out of the surfaces created in RAM. For example: one group of triangles is created for the fuselage, another group for the upper surface of the wing, one more for the lower surface of the wing, and another set for the wing end cap. These triangle groups can then be tracked throughout GTS to ascertain the RCS contribution of each surface. If the RCS of an aircraft is too high to meet a given constraint, then the designer could examine groups of triangles or even the triangles themselves to determine which is creating a hotspot of RCS. Another benefit is that scripts exist to adjust the grid spacing. Since GTS requires that each panel be at least 1.5 times the wavelength of the threat radar, the grid should be of the proper size. Moreover, grid visualization tools have been linked to the code, thus easing troubleshooting.

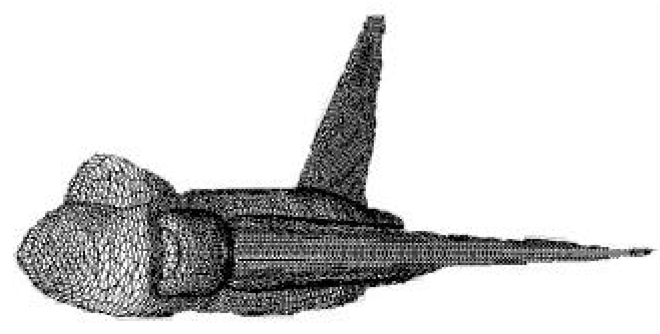

Figure 12: Surface Grid Generated by FELISA

There are also a few items on the downside. As with all CFD/grid tools, robustness may be an issue. Previous experience has shown that grid generation tools do not work for all geometries. Small changes in configuration produce errors within the codes, causing them to crash. Previous attempts at using CFD within a DOE have found runtime to be a limiting factor. At this time, no code better than FELISA has been identified.

SIGNATURES ANALYSIS

The triangles created by FELISA are translated into a MAX input file by a program of the author's own design. This program maintains the groups created by FELISA for maximum utility. After running MAX as a translator to create a binary GTS input file, GTS is run to analyze the geometry. GTS creates a binary output file that needs to be post-processed to extract the data and format them in a useful manner. Please refer to the sections above for further details on the inner workings of GTS and MAX.

In addition to geometry, RCS analysis depends on several factors. Frequency is quite important. As discussed above, the frequency range of 8 to 18 GHz is most likely to be encountered as a threat. In addition, RCS is a function of both azimuth and elevation, the direction from the vehicle to the threat radar. Positioning the vehicle at a mesh of specific points provides data over the expected threat regions. While it is possible to calculate the RCS of a vehicle for all viewing angles, runtime is prohibitive. The fineness of the analysis mesh will be investigated for its impact on probability of detection, measures of effectiveness, data visualization, and runtime. Finally, material properties affect RCS. It is possible to input different material constants for each panel in a vehicle. Customizing the panel characteristics would reduce RCS. However, this is a second order effect.

POST PROCESSING

The goal of post processing is to extract data from the RCS analysis output files, format it in a table, and present it in a visual manner. Extracting the data from the GTS output files is straight forward as is presenting the data in a tabular format. Data visualization is not be as easy. At the minimum it will is necessary to plot RCS “fuzzballs”, RCS as a function of viewing angle for a given planar slice (elevation=0°) as seen in Figure 13. This figure shows the RCS for the nose on direction, at 0°, with the RCS from the left of the vehicle at 90°. Other visualization techniques have been developed to show the effects of 3D data, data as a function of azimuth and elevation. Figure 14 shows a visualization format where RCS is plotted versus azimuth and elevation. RCS is along the z-axis while azimuth and elevation are along the x and y axes. Color is also used to represent RCS magnitude. Figure 15 presents a third visualization format developed for this work. RCS is plotted as a color for return intensity on a sphere. Points on the sphere represent a direction from the vehicle to a threat and the color represents the magnitude of the RCS for the vehicle at that angle. This figure shows the RCS for a ±30° frontal sector for a generic fighter (axes provided for reference). Perhaps visualization techniques could be developed for the fourth dimension, frequency, as well.

Below, Table 4 summarizes the codes selected for each step in the methodology. Together with the above descriptions, it should be clear which tools, techniques, and methods have been used to construct a parametric tool for RCS prediction for the conceptual design environment.

CONCLUSIONS

A preliminary methodology for bringing signatures analysis upstream and making it part of the conceptual design phase has been presented along with options for codes to perform the analyses.

However, the primary contribution of this work is not in the selection of specific codes. The codes recommended here are only used to illustrate the concept methodologies and were chosen based on a compromise between ease of use, capability, runtime, and availability. A primary importance of this work, is the ability for the methodology to work at various levels of fidelity. The same methodology developed here would

Title:
/home/asdl1/sig/tests/radargram2.eps
Creator:
MATLAB, The Mathworks, Inc.
Preview:
This EPS picture was not saved
with a preview included in it.
Comment:
This EPS picture will print to a
PostScript printer, but not to
other types of printers.

Figure 13: RCS Radargram

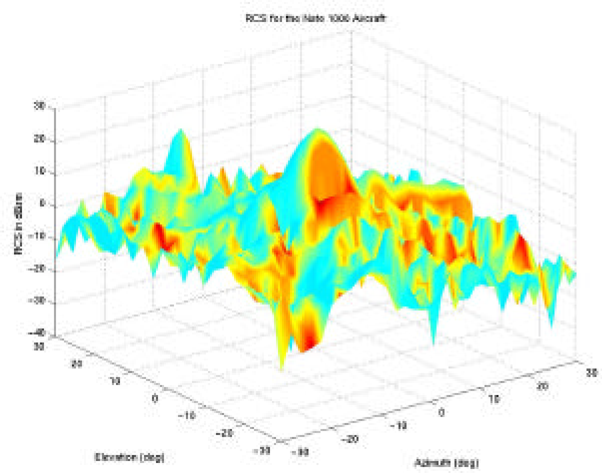

Figure 14: RCS Carpet Plot

work at a much higher level of fidelity if more information were supplied at each level of the analysis. For example, if the 3D model contained more detailed geometry and materials descriptions, the RCS analysis were more detailed in the types of scattering examined, and the threat information more specific, classified level results could be obtained. Furthermore, this methodology has the built in capability for expansion. IR analysis and other signature analyses, aerodynamics, propulsion, and other traditional discipline analyses could be included for a more complete synthesis and sizing tool.

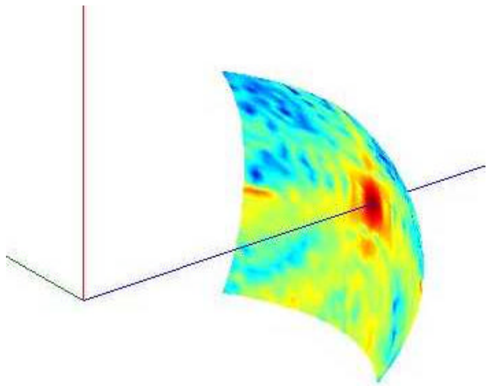

Figure 15: RCS Sphere Plot

Table 4: Summary of Codes

Purpose of Code	Code Name
Parametric CAD	RAM
Surface Tessellation	FELISA
Translate Triangles for RCS Analysis Input	MAX
RCS Analysis	GTS
Data Visualization / Processing	MATLAB

Now that a parametric RCS analysis system has been developed, future work will include utilizing the tool for various system level studies. The relative importance of shaping parameters will be examined. Different shaping schemes could be investigated. Signature requirements could be examined for their effect on aircraft geometry. Furthermore, the geometry dependent signatures information could be provided to a campaign analysis to show the change in system effectiveness due to changes in planform. Analysis at this level will provide insight into the system of systems problem of campaign analysis. The analysis tool described in this paper is but a stepping stone in a path of future work.

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DEFINITIONS

λ	Wavelength
σ	Radar Cross Section (RCS)
π	Pi=3.1415…
E_i	Incident energy
E_s	Energy from the scatterer
G	Gain of the radar
L	Loss factor
P_h	Probability of being hit
$P_{k\|h}$	Probability of being killed if hit
P_s	Probability of survivability
P_t	Power transmitted by the radar
P_{min}	Power threshold minimum for detection
R	Radius

ACRONYMS

ASDL	Aerospace Systems Design Laboratory
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
DOE	Design of Experiments
GCL	GTS Command Language
GHz	GigaHertz (1 x 10^9 Hz)
GT	Georgia Institute of Technology
GTRI	Georgia Tech Research Institute
GUI	Graphical User Interface
HSCT	High Speed Civil Transport
IR	InfraRed
JSF	Joint Strike Fighter
LO	Low Observable
MCL	MAX Command Language
MHz	MegaHertz (1 x 10^6 Hz)
OEC	Overall Evaluation Criteria
ONR	Office of Naval Research
OO	Ordinal Optimization
RAM	Rapid Aircraft Modeler or Radar Absorbing Material
RCS	Radar Cross Section
RCSR	Radar Cross Section Reduction
RDS	Robust Design Simulation
RSE	Response Surface Equation
RSM	Response Surface Methodology
SAM	Surface to Air Missile
SNR	Signal to Noise Ratio
TIES	Technology Identification Evaluation and Selection